Calculation of the vectorial field distribution in stratified media for high NA-systems

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For a sensible interpretation of the image formation and information retrieval in optical far- and near-field microscopy, lithography and optical recording, it is essential to have a good understanding of the field used for illumination of the sample or data structure. Due to the demand for an ever increasing resolution, the wavelength of the used light decreases to the ultraviolet and the numerical aperture of the imaging systems used for illumination and imaging has approached its theoretical limit. The field distribution in the focal region of a homogeneous medium can be obtained with the well-known diffraction integrals given by Richards and Wolf[1]. However, in general the sample is placed in a multilayered environment, where one or more medium transitions should be taken into account as was done in Refs[2-4]. These theoretical descriptions of the multilayer systems are fully vectorial and valid for a high numerical aperture imaging system and have each their own advantages and disadvantages.

We use a different and, we believe, more transparent picture to obtain the formulae necessary to calculate the field distributions in each layer of the stratified medium, which describes the changes in orientation of the electric field vector due to the lens or due to the transition to another medium. The algorithm discussed in this paper is easy to implement and is fast in operation since only a one dimensional integral should be evaluated numerically.

The electric field distribution in medium i is given by

$$\mathbf{E}_i(\mathbf{r}) = -\frac{iR}{2\pi}\int_0^{2\pi}\int_0^{\mathrm{NA}k_0} \frac{e^{irk_r\cos(k_\phi-\phi)}}{\sqrt{k_{z1}k_1}}\left[e^{ik_{zi}z}\mathbf{M}_i^+ + e^{-ik_{zi}z}\mathbf{M}_i^-\right]\cdot\mathbf{E}_0(k_r,k_\phi)k_r dk_r dk_\phi \quad , \qquad (1)$$

where R denotes the focal length, the propagation vector $\mathbf{k} = (k_r, k_\phi, k_{zi})$ as well as the position vector $\mathbf{r} = (r, \phi, z)$ are given in cylindrical coordinates. The subscript i denotes the medium in which each quantity is located. The propagation matrices $\mathbf{M}_i^\pm$ include both the lens operation and the geometry of the focal region, the positive or negative sign is related to traveling waves in the forward or backward direction, respectively. The numerical aperture is denoted by NA and the wave number of vacuum by k_0.

To demonstrate the strength of our algorithm, we present an example which concerns an immersion lens (NA = 1.4) which operates slightly out of contact with the sample.

In conclusion, we believe that with the presented method, several problems related to far- and near-field optical microscopy, lithography and optical recording can be analysed in detail with our transparent and efficient calculation scheme.

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